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Annealing of Radiation Damage in 0.1- and 2-ohm-Centimeter Silicon Solar Cells

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and Space Administration

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SUMMARY

Isochronal and isothermal annealing studies were conducted on 0.1- and 2-ohm-centimeter n^+/p silicon solar cells after irradiation by 1-MeV electrons at fluences (φ) of 10^{14}, 5×10^{14}, and 10^{15} per square centimeter. For the 0.1-ohm-centimeter cells, reverse annealing was not observed in the isochronal data. However, reverse annealing was observed between approximately 200° and 325° C in the isochronal data of the 2-ohm-centimeter cells. Isothermal annealing of 0.1-ohm-centimeter cells at 500° C restored pre-irradiation maximum power (P_{max}) within 20 minutes at $\varphi = 10^{14}$, in 180 minutes at $\varphi = 5\times10^{14}$ and to 92 percent of pre-irradiation P_{max} in 180 minutes for $\varphi = 10^{15}$. Annealing at 450° C was found inadequate to restore 0.1-ohm-centimeter cell performance within reasonable times for all fluence levels. By comparison, at 450° C, the P_{max} of 2-ohm-centimeter cells was restored within 45 minutes, for the two highest fluence levels, while for the lowest fluence, restoration was completed within 15 minutes.

Spectral response data indicate that for both resistivities degradation occurs predominantly in the cells p-type base region.

INTRODUCTION

Theoretical calculations predict that 0.1-ohm-centimeter n^+/p silicon solar cells can attain air-mass-zero (AM0) beginning-of-life efficiencies as high as 19 percent (refs. 1 to 3). However, it was found, by irradiations performed on 0.1-, 2-, 5-, and 9-ohm-centimeter cells, that the 0.1-ohm-centimeter cells experienced greater radiation induced degradation than was the case for the higher resistivity cells (ref. 4). Thus the problem of degradation from high initial performance levels, due to the particulate space radiation, becomes more serious for the low resistivity cells.

It is well known that cell performance that has been degraded by radiation can be restored, partially or fully, by thermal annealing (refs. 5 and 6). While annealing data exist for cells of resistivity 1 ohm-centimeter and greater (refs. 5 and 6), no annealing data have been reported for 0.1-ohm-centimeter cells.

The results of our initial thermal annealing experiments with 0.1-ohm-centimeter cells are presented in this paper. Annealing data are also presented for 2-ohm-centimeter cells for comparison with the annealing behavior of the lower resistivity cells.

EXPERIMENTAL PROCEDURES

The 0.1-ohm-centimeter n^+/p silicon solar cells were fabricated at Lewis; while the 2-ohm-centimeter cells were obtained commerically. The starting material for the 0.1-ohm-centimeter cells was boron-doped p-type, float zone silicon, while the 2 ohm-centimeter cells were Czochralski-grown p-type single crystal silicon. The cell junctions for the 0.1-ohm-centimeter cells were formed by gaseous diffusion, the wafers being heated at 950° C for 60 minutes in phosphorus oxytrichloride. After p-n junction formation, silver-aluminum front and back electrical contacts were vacuum deposited on the cells. Thickness of both the 0.1- and 2-ohm-centimeter cells was 250 micrometers.

Room-temperature irradiation with 1-MeV electrons was performed in air at the Lewis electron accelerator. Two cells of each resistivity were irradiated at each of three fluence levels: 10^{14}, 5×10^{14}, and 10^{15} electrons per square centimeter. For postirradiation annealing the cells were heated in a quartz tube through which a constant flow of helium gas was maintained. For each fluence level one cell of each resistivity was subjected to an isochronal anneal during which the temperature was varied in 50° C steps. After completion of the isochronal anneal the remaining unannealed cells were isothermally annealed at 450° and 500° C, respectively. These latter two temperatures were chosen on the basis of the annealing behavior observed during the isochronal anneal. Before and after irradiation and during the course of both anneals, AM0 current-voltage data were obtained using a xenon-arc solar simulator. Spectral-response data were obtained using a filter-wheel spectral-response apparatus (ref. 7).

RESULTS AND DISCUSSION

Isochronal Annealing

The isochronal annealing data are shown in figure 1 where ΔI_{sc}, the percent change in short circuit current, is plotted against temperature with

$$\Delta I_{sc} = \frac{(I_{sc})_B - (I_{sc})_A}{(I_{sc})_B} \times 100\% \qquad (1)$$

where $(I_{sc})_B$ is cell short-circuit current at AM0 before irradiation and $(I_{sc})_A$ is the AM0 short-circuit current of the irradiated cells after annealing for equal times (20 min) at each fixed temperature. The experimental error in each measurement of I_{sc} is ±1 percent. Hence, the resultant error in ΔI_{sc} is ±1.41 percent.

As shown by the figure, the isochronal annealing data exhibit reverse annealing for the present 2-ohm-centimeter cells between approximately 200° and 325° C. However, within the experimental error, reverse annealing is not observed in the present 0.1-ohm-centimeter cell data. Reversal during isochronal anneal has been reported previously for cells with resistivities varying between 1 and 25 ohm-centimeters after irradiation by 1-MeV electrons at room temperature (refs. 5 and 6). Isochronal annealing data from reference 6 are included in figure 1(a) for a 1-ohm-centimeter cell which had been irradiated with 1-MeV electrons, at room temperature, to $\varphi = 10^{15}$ per square centimeter. The reverse annealing for the 1-ohm-centimeter cell begins at approximately the same temperature as the reverse anneal in the present 2-ohm-centimeter cell. However, the behavior of the reverse anneal above 200° C for the 1-ohm-centimeter cell differs from that observed for the present 2-ohm-centimeter cells. The reasons for this and for the absence of reverse annealing in the 0.1-ohm-centimeter cell data are not clear at present.

In addition to reverse annealing, the data of figure one show that, for a given fluence, increased boron content is accompanied by increased radiation-induced degradation. Increased boron content also leads to radiation-induced degradation requiring higher annealing temperatures for restoration. Also, for cells of equal boron content, higher fluences result in higher radiation-induced degradation and a consequent requirement for higher annealing temperatures.

The isochronal annealing data suggest that the 0.1-ohm-centimeter cells should be readily annealed at 550° C. However, it was found that cell contact degradation occurred near this temperature. Hence, 500° C was selected as the maximum, safe isothermal annealing temperature for the 0.1-ohm-centimeter cell. For the 2-ohm-centimeter cells the isochronal data suggests that these cells should readily isothermally anneal at 450° C.

Isothermal Annealing

As suggested by the isochronal annealing data, the 2-ohm-centimeter cells were isothermally annealed at 450° C. While the 0.1-ohm-centimeter cells were annealed at 500° and 450° C. The isothermal annealing data are shown in figure 2 where ΔP_{max}, the percent change in cell maximum power is plotted against annealing time with

$$\Delta P_{max} = \frac{(P_{max})_B - (P_{max})_t}{(P_{max})_B} \times 100\ \% \qquad (2)$$

where $(P_{max})_B$ is cell maximum power, at AM0, measured before irradiation and $(P_{max})_t$ is cell maximum power, at AM0, after annealing for a time t at a fixed temperature. The experimental error in P_{max} is approximately ±1 percent. Hence, the resultant estimated error in ΔP_{max} varies between ±1.2 and ±1.4 percent.

For the 0.1-ohm-centimeter cells, annealed at 500° C (fig. 2(a)), at $\varphi = 10^{14}$ per square centimeter, annealing is completed withn 20 minutes. For $\varphi = 5\times10^{14}$ per square centimeter, within the experimental error, P_{max} is restored to its unirradiated level in 180 minutes, while for $\varphi = 10^{15}$ per square centimeter P_{max} is restored to 92 percent of its unirradiated value at this time. Extrapolation of the latter data indicates that for $\varphi = 10^{15}$ approximately 300 minutes would be required to restore the initial, unirradiated P_{max} value.

As expected from the isochronal annealing data, the 0.1-ohm-centimeter cells do not completely recover at 450° C (fig. 2(b)). Because the recovery rate was so slow, the annealing was terminated after 105 minutes. At this time, for $\varphi = 10^{15}$ restoration to 66 percent of the unirradiated P_{max} occurs; for $\varphi = 5\times10^{14}$ restoration to 79 percent occurs, while for $\varphi = 10^{14}$ P_{max} recovers 92 percent of its unirradiated value.

Comparison of figures 2(a) and (b) shows a large difference between the ΔP_{max} values after irradiation, and before annealing, for the 0.1-ohm-centimeter cells 653-14 and 653-16. Although both cells were irradiated at the same fluence level, cell 653-14 developed a 7 percent increase in fill factor after irradiation while all other cells exhibited a small decrease in fill factor after irradiation. Hence, the large difference in initial ΔP_{max} values is attributed to the unusual increase in fill factor. (This could possibly be due to contact problems in cell 653-14). For the remaining cells of equal resistivities, the smaller differences in initial ΔP_{max} values, for equal fluences, are attributed to individual cell differences, no two cells being exactly alike. This is illustrated by the data of table I, where the pre-irradiation values of the solar-cell parameters are listed for all six cells undergoing isothermal anneal.

Spectral-response curves for a 0.1-ohm-centimeter cell, isothermally annealed at 500° C, and a 2-ohm-centimeter cell, isothermally annealed at 450° C, are shown in figures 3 and 4. From the figures, it is seen that, for both resistivities, radiation predominantly affects the long wavelength response. From this it is concluded that the radiation induced degradation occurs predominantly in the cells' p-base region.

SUMMARY OF RESULTS

Isochronal and isothermal annealing studies were conducted on 0.1- and 2-ohm-centimeter n^+/p silicon solar cells irradiated with 1-MeV electrons to fluences (φ) of 10^{14}, 5×10^{14}, and 10^{15} per square centimeter. For the 0.1-ohm-centimeter cells

reverse annealing was not observed, within experimental error, in the isochronal annealing data. However, reverse annealing was observed between approximately 200° and 325° C in the 2-ohm-centimeter isochronal data at all fluence levels.

The isothermal annealing behavior of the irradiated 0.1-ohm-centimeter cells was determined at 500° and 450° C. With respect to the 500° C anneal, at $\varphi = 10^{15}$ per square centimeter P_{max} was restored to 92 percent of the pre-irradiation level after 180 minutes, with 300 minutes being the time estimated for complete recovery. At $\varphi = 5\times10^{14}$ per square centimeter P_{max} recovery was essentially complete after 180 minutes, while for $\varphi = 10^{14}$ per square centimeter recovery was complete within 20 minutes. For the 450° C anneal at 105 minutes; at $\varphi = 10^{15}/cm^2$, P_{max} was restored to 66 percent of the pre-irradiation level; at $\varphi = 5\times10^{14}$ recovery to 79 percent of the unirradiated level occurs while for $\varphi = 10^{14}/cm^2$ restoration to 92 percent of pre-irradiation P_{max} was observed. At 450° C, for the 0.1-ohm-centimeter cells little further recovery is noted around 105 minutes. Hence the time for complete recovery of these low resistivity cells cannot be estimated from the present data.

For the 2-ohm-centimeter cells, annealing at 450° C was found adequate to restore performance at all fluence levels. At this temperature, recovery was complete within 45 minutes for the two highest fluences while at the lowest fluence P_{max} recovery was complete within 15 minutes.

For both the 0.1- and 2-ohm-centimeter cells, spectral response data indicate that radiation induced degradation occurs predominantly in the cells' p-type base region.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 7, 1979,
506-23.

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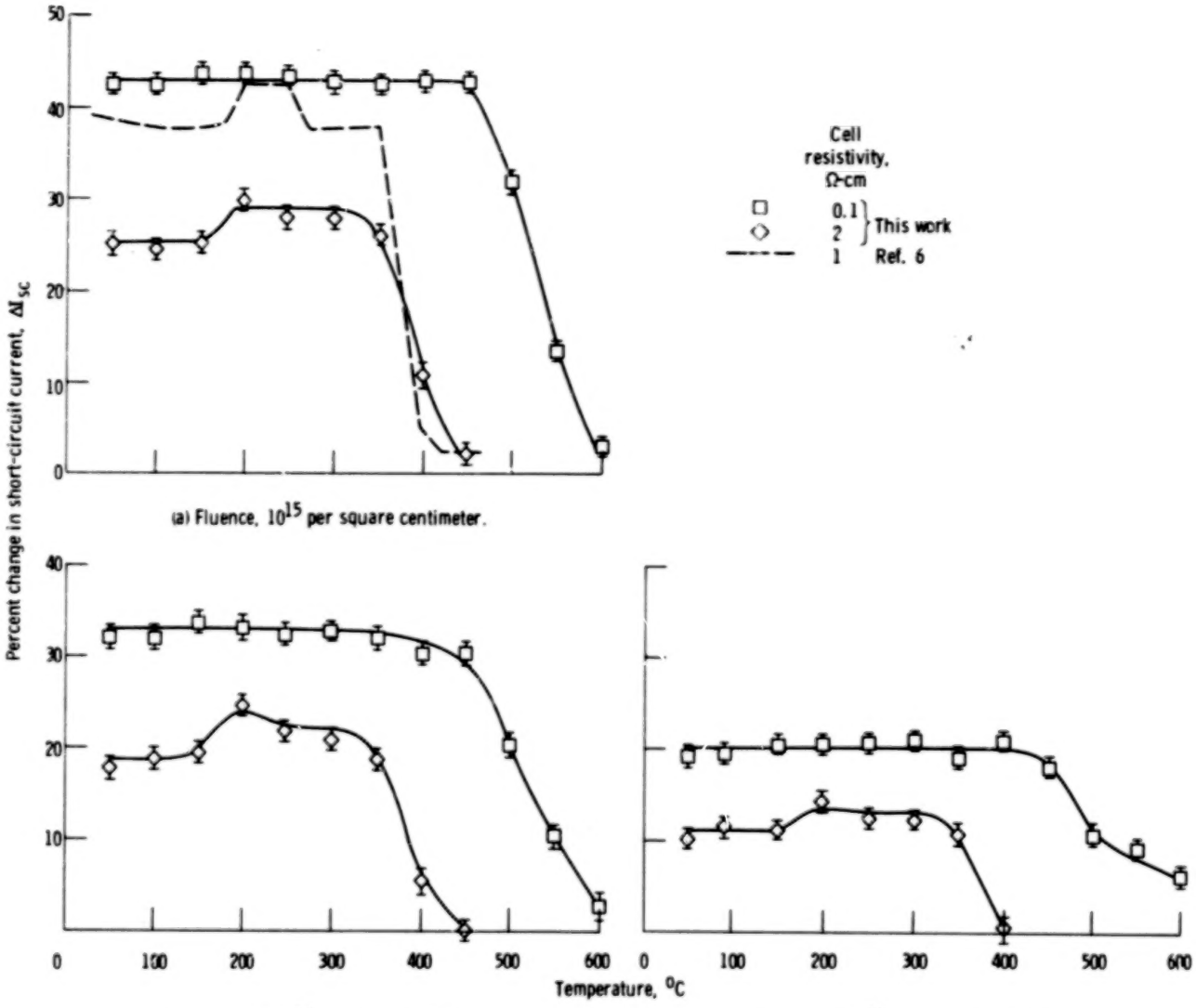
TABLE I. - PRE-IRRADIATION SOLAR CELL PARAMETERS, RADIATION FLUENCES, AND ANNEALING TEMPERATURES

Cell number	Resistivity, Ω-cm	Maximum power P_{max}, mW	Short-circuit current I_{sc}, mA	Voltage, V_{oc}, mV	Fill factor, percent	Annealing temperature, °C	1-MeV electron fluence, φ, cm^{-2}
653-7	0.1	37.7	75.6	612	81.4	500	1×10^{15}
653-11	↓	33.0	72.3	607	75.2	500	5×10^{14}
653-14	↓	30.4	68.6	603	73.5	500	1×10^{14}
653-3	↓	34.8	70.2	608	81.5	450	1×10^{15}
653-12	↓	39.0	78.3	613	81.1	↓	5×10^{14}
653-16	↓	31.8	67.8	604	77.5	↓	1×10^{14}
C-1-20	2	37.3	85.3	573	76.4	↓	1×10^{15}
C-2-10	2	36.6	89.0	572	71.9	↓	5×10^{14}
C-2-17	2	37.4	85.5	570	76.7	↓	1×10^{14}

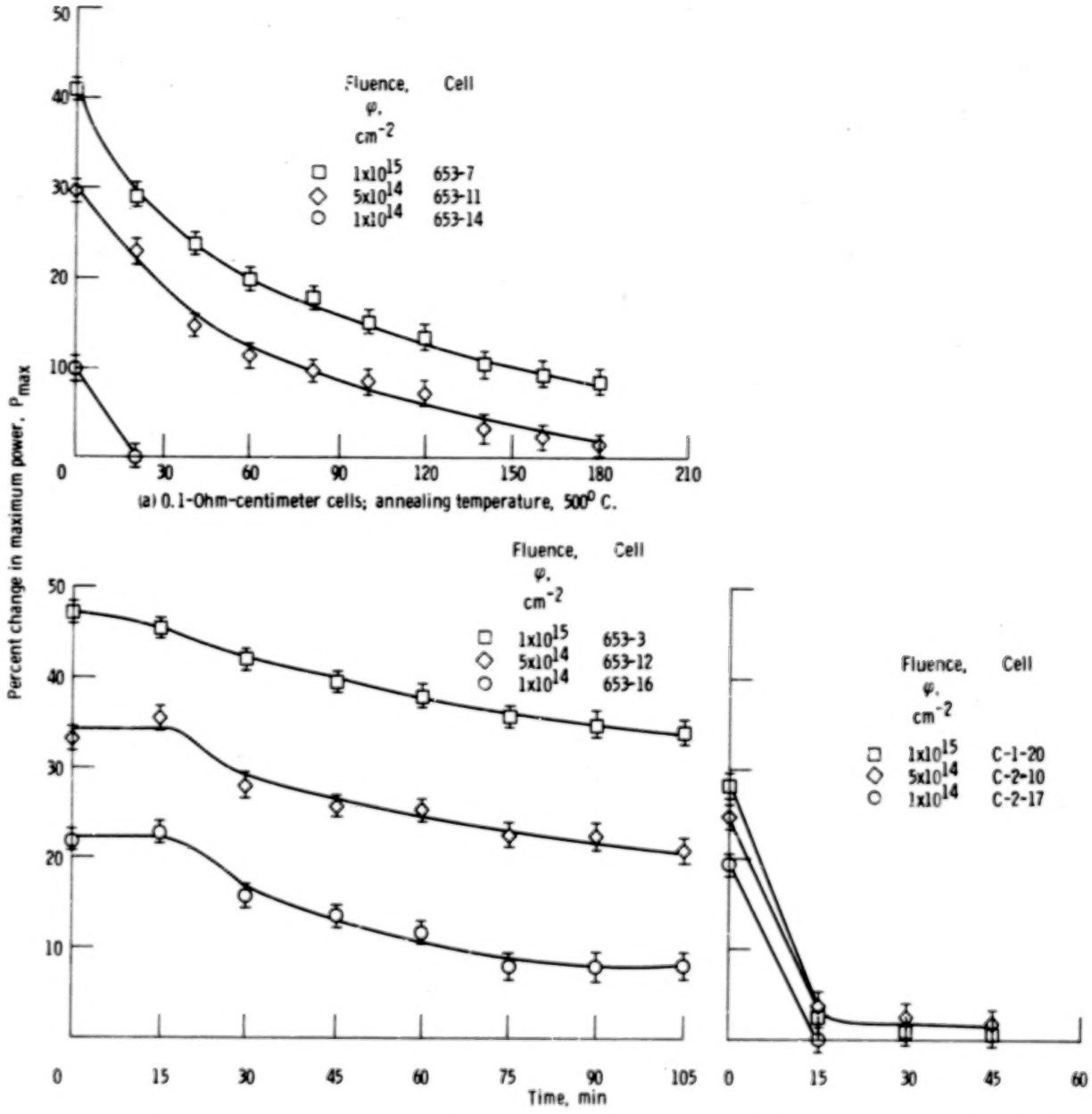


(a) Fluence, 10^{15} per square centimeter.

(b) Fluence, 5×10^{14} per square centimeter.

(c) Fluence, 10^{14} per square centimeter.

Figure 1. - Isochronal anneal of silicon solar cells after 1-MeV electron irradiation. Time at temperature, 20 minutes.



(a) 0.1-Ohm-centimeter cells; annealing temperature, 500° C.

(b) 0.1-Ohm-centimeter cells; annealing temperature, 450° C.

(c) 2-Ohm-centimeter cells; annealing temperature, 450° C.

Figure 2. - Effect of isothermal annealing (P_{max} recovery after irradiation with 1-MeV electrons).

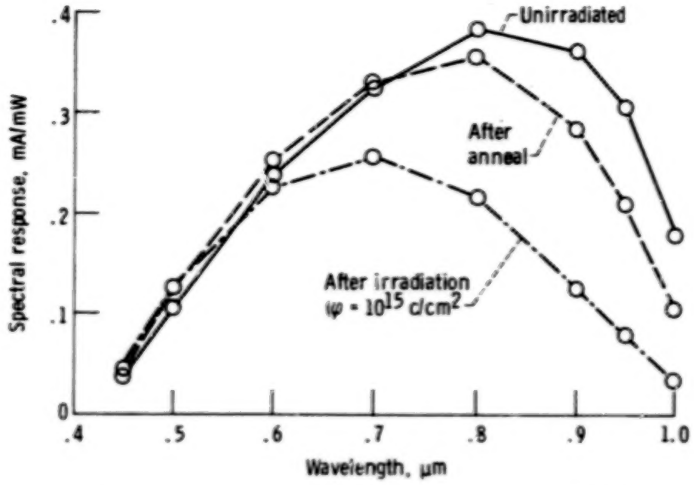


Figure 3. - Spectral response of 0.1-ohm-centimeter cell (no. 653-7) before and after irradiation and after annealing for 180 minutes at 500° C.

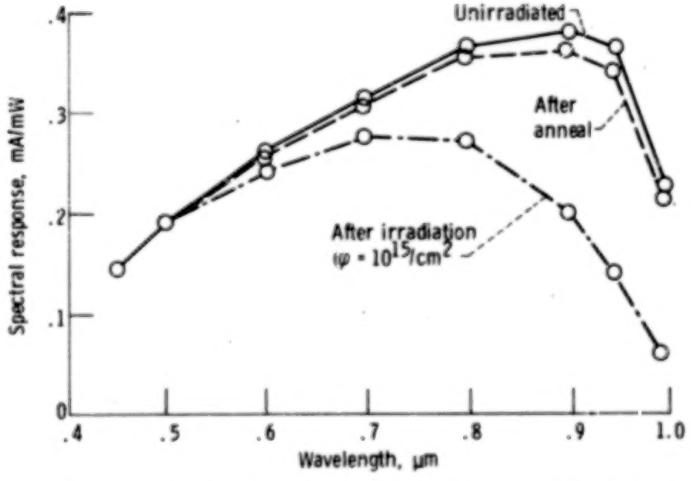


Figure 4. - Spectral response of 2-ohm-centimeter cell (no. C-1-20) before and after irradiation and after annealing for 45 minutes at 450° C.

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16. Abstract

Isochronal and isothermal annealing studies were conducted on 0.1- and 2-ohm-centimeter n^+/p silicon solar cells after irradiation by 1-MeV electrons at fluences (φ) of 10^{14}, 5×10^{14}, and 10^{15} per square centimeter. For the 0.1-ohm-centimeter cells, reverse annealing was not observed in the isochronal data. However, reverse annealing was observed between approximately 200° and 325° C in the isochronal data of the 2-ohm-centimeter cells. Isothermal annealing of 0.1-ohm-centimeter cells at 500° C restored pre-irradiation maximum power (P_{max}) within 20 minutes at $\varphi = 10^{14}$, in 180 minutes at $\varphi = 5\times10^{14}$ and to 92 percent of pre-irradiation P_{max} in 180 minutes for $\varphi = 10^{15}$. Annealing at 450° C was found inadequate to restore 0.1-ohm-centimeter cell performance within reasonable times for all fluence levels. By comparison, at 450° C, the P_{max} of 2-ohm-centimeter cells was restored within 45 minutes, for the two highest fluence levels, while for the lowest fluence, restoration was completed within 15 minutes. Spectral response data indicate that, for both resistivities, degradation occurs predominantly in the cells p-type base region.

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